Docket No. 1252.1053

TITLE OF THE INVENTION

A SYSTEM OF FEATURE-BASED SURFACE MAPPING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is related to and claims priority to U.S. application entitled "Feature-based displacement mapping", having serial number 60/290,669, by Jerome Maillot and Xiaohuan Wang, filed May 5, 2001 and incorporated by reference herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0002] The present invention is directed to displacing or offsetting surfaces and, more particularly, to a system that provides a higher density of tessellation where detail of the object is the greatest.

2. Description of the Related Art

[0003] In the field of computer graphics, there are various approaches to adding visual complexity to a surface. Texture mapping and bump mapping have been used to add visual effects to surfaces. Bump mapping perturbs surface normals but does not alter the actual surface geometry, causing artifacts that are particularly noticeable from silhouette views. Both approaches leave the actual geometry of the surface smooth and unaltered, regardless of the complexity of the mapping. Shadowing and reflection are also problematic. These problems can be avoided by altering the surface geometry to add detail or complexity to the surface. This approach, called displacement mapping, avoids shortcomings related to texture and bump mapping.

[0004] A displacement map is a way of using a scalar height field $h(x,y)$ to specify an offset surface $S'(x,y)$. Given a surface $S(x,y)$ with normal field $N(x,y)$, the offset surface is defined as $S'(x,y) = S(x,y) + h(x,y)N(x,y)$. This offsetting operation presents numerous problems, including problems in performing the offset operation, and problems with the final offset surface, which is usually a polygonal mesh.

[0005] In rendering applications, surfaces are often represented by meshes, whereas height fields are often represented by parametric mappings that are unrelated to the surface. One way of offsetting a mesh surface is to simply displace vertices of the mesh according to the height field and the normals of the surface. However, the resulting offset surface mesh will have a vertex density on the order of the original surface. As a result, a vertex-sparse original mesh often results in a displaced mesh that has too few vertices to accurately represent complex

features of the height field, such as curves and edges, resulting in an undersampled or coarse offset surface. Furthermore, offsetting a vertex-dense original mesh requires increased computing resources, and often results in a displaced mesh that has more vertices than are necessary to portray the features and complexity of the height field. The number of unnecessary vertices in a vertex-dense offset mesh is usually significant, and impractical or impossible computing resources are often required to store and manipulate the mesh. Furthermore, even vertex-dense meshes often contain artifacts such as stripes, cracks, and zippers.

[0006] Micropolygon decomposition is another unsatisfactory displacement approach. Figure 1 shows a surface displaced with micropolygon decomposition 50. This approach tessellates each surface into polygons that are smaller than a quarter of a screen pixel. Because geometry is rendered in surface order, clipped to the size of screen tiles, and then immediately purged once shaded, the practical incurred memory cost of an otherwise explicitly high polygon density from such a tessellation is minimal. However, this approach produces cracks, and produces stretched polygons for rapidly varying displacement maps.

[0007] Simplifying a dense offset mesh is also not satisfactory because large amounts of temporary memory are still required to store the initial dense offset mesh. Furthermore, high tessellation densities may be initially encountered, even where the displacement features are sparse.

[0008] What is needed is an efficient displacement mapping technique that produces high-quality displacement mapped surfaces that optimally represent the features and complexity of the displacing height field.

SUMMARY OF THE INVENTION

[0009] It is an aspect of the present invention to provide a system for generating a high-quality offset surface that is independent of the mesh density of the original displaced surface.

[0010] It is another aspect of the present invention to provide a system for generating a high-quality surface based on features of the surface.

[0011] It is another aspect of the present invention to provide a system for generating a surface that uses a minimal set of vertices to accurately represent the features and complexity of the surface.

[0012] It is an aspect of the present invention to provide a system capable of supporting the traditional workflow approach of surface layering, as for example with the application of shading and texturing surfaces.

[0013] It is another aspect of the present invention to provide a system efficient enough at displacement mapping to generate offset surfaces on-the-fly in a rendering setting, and capable of use in real-time and ray-tracing contexts.

[0014] It is another aspect of the present invention to provide a system for displacement mapping that generates offset surfaces that are suitable for rendering with quality comparable to existing and future rendering packages.

[0015] It is another aspect of the present invention to provide a system for generating offset surfaces of an original surface by producing a mesh that both accurately approximates the offset surface and that uses a minimal number of vertices.

[0016] It is another aspect of the present invention to provide a system for generating offset surfaces of an original surface by producing a mesh that avoids artifacts while using a minimal number of vertices.

[0017] It is another aspect of the present invention to provide a system for generating accurate, optimal density, high-quality offset surfaces without requiring large amounts of temporary memory.

[0018] It is another aspect of the present invention to provide a system for generating accurate, optimal density, high-quality offset surfaces while preserving the parts of the original surface that are not displaced.

[0019] It is another aspect of the present invention to provide a system for displacing a surface, where the resolution of the displacement may be dynamic, based on viewpoint, based on different values in different user-selected regions, based on feature size, based on resolution size, based on vertex density, and or based on ratios of the aforementioned other bases.

[0020] The present invention provides the above aspects by analyzing a model to determine the level of detail in the model. Where the level of detail is high the number of polygons, typically triangles, used to represent the high detail area is increased through the use of "sub-triangles". The positions of the sub-triangles are also strategically located and constrained to better represent the high detail area, particularly any edges in the area. The level of detail can

be determined using a displacement map for the surface. The positions of the triangles can be located by determining feature points (or sub-triangle vertices) in the areas of detail where the feature points can be moved toward the areas of high rate of change and additional feature points can be added. The feature points can be connected to form the sub-triangles with an emphasis or constraint on connecting points along an edge or border.

[0021] The above aspects can also be attained by a system that displaces a surface by tessellating the surface into a first set of triangles, where the tessellation has a fineness, according to the size of the triangles, that is sufficient to represent the surface, but not sufficient to represent detail in a displacement map.

[0022] A set of points for each triangle in the first set may be derived by creating a non-orthogonal coordinate system defining a grid of points on and in the triangle, wherein the two shortest sides of the triangle are axes of the coordinate system and the triangle vertex where the axes intersect is the origin of the coordinate system. Height values for most of the points may be calculated by sampling a height field. A feature metric may be calculated for most of the points in a triangle by summing Taylor approximations taken in directions of points neighboring a point, where the Taylor approximations are calculated using the height values of the neighboring points, and where the feature metric approximates an amount of local curvature in the height field in a local area of the point. Points that have a feature metric indicating that the point is in a substantially locally flat area of the height field may be discarded.

[0023] A feature orientation may be calculated for the points that were not discarded by using a least squares minimization to fit a linear function to a plurality of points neighboring the point, where the feature orientation is a discrete gradient of the height field that approximates a direction from the point that has the greatest rate of local height change. The height field may be further sampled at points uniformly distributed along a line segment within a point's neighborhood, where a line segment passes through its point in the direction of the feature orientation of the point, and where a rate of height change in the height field along the line segment is approximated for the point and each sample point by using their height field values.

[0024] Points may be relocated to the location of the closest sample point on the line segment that has a rate of height change above a given threshold, and points may be added at sample points on the line segment having a rate of height change indicating an extrema or feature in the height field.

[0025] A second set of triangles may then be created by constraining a Delaunay triangulation of the set of points of each triangle in the first set of triangles, where a constraint is a feature border of the height field in the triangle that is identified by the set of points. A final displaced surface geometry may be built using the second set of triangles.

[0026] These together with other aspects and advantages which will be subsequently apparent, reside in the details of construction and operation as more fully hereinafter described and claimed, reference being had to the accompanying drawings forming a part hereof, wherein like numerals refer to like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] Figure 1 shows a surface displaced with micropolygon decomposition 100.

[0028] Figure 2 shows a flowchart of a method according to an embodiment of the invention.

[0029] Figure 3 shows an original surface 80 including a sinusoidal wave displacement area 82 colored white, and a non-displaced area 84 colored black.

[0030] Figure 4 shows a two-triangle original tessellation of the original surface 80 seen in Fig. 3.

[0031] Figure 5 shows an example of a triangle 100 in an original tessellation, where the triangle has a sample point grid, defined by axes 102, 104, and origin point 106, that is used in generating a height map for the triangle.

[0032] Figure 6 shows a triangle 120 with a grid based on an inferior origin 122 that is not opposite the longest side of the triangle 120, resulting in a grid that exhibits more oblique distortion than the grid in Fig. 5.

[0033] Figure 7 shows triangle 120 with sample point $P_{i,j}$ that has a local neighborhood 130.

[0034] Figure 8 shows triangle 120 with a sample point $P_{i,j}$ (gray) having neighboring points N(1) (hollow) and N(2) (black).

[0035] Figure 9 shows four lines 140 defined by $P_{i,j}$ and its N(1) neighborhood.

[0036] Figure 10 shows a surface 150 generated with triangles that have had sample points removed based on their feature metric, but where the triangles have not been feature-adjusted.

[0037] Figure 11 shows a surface 160 generated with triangles used to generate Fig. 10, but with feature points adjusted (added and moved) based on features located with feature

orientations.

[0038] Figure 12 is a view above sample points in a triangle, showing the 8 neighborhood points N(1) (peripheral solid points) of sample point $P_{i,j}$, and a line segment $L_{i,j}$ which passes through the sample point $P_{i,j}$ in the direction of $P_{i,j}$'s feature orientation $o_{i,j}$, and on which are shown; the original position of the sample point (hollow circle $P_{i,j}$), the 2m (8) height samples (grey points P_{2m}), two of which are the adjusted location of $P_{i,j}$ (gray circle $P'_{i,j}$) and the sample point added at an extrema of line $L_{i,j}$ (gray square point $P''_{i,j}$).

[0039] Figure 13 is a profile view of Fig. 12, showing the curvature of line $L_{i,j}$ in the height field with points corresponding to those in Fig. 12.

[0040] Figure 14 shows a plane surface 180 displaced with a ring texture or displacement map, where feature points in triangles were moved according to their feature orientation but where new feature points were not added at extrema.

[0041] Figure 15 shows the image of Fig. 14 after vertices have been added to extrema on $L_{i,j}$, thereby improving the representation of the profile and base of the ring.

[0042] Figure 16 shows a displaced surface 200 with cracks 202 produced by a standard Delaunay triangulation.

[0043] Figure 17 shows a closer view of the cracks 202 shown in Fig. 16, as seen from another angle.

[0044] Figure 18 shows a view of surface 220 with edges 222 (white lines) defined by a feature border.

[0045] Figure 19 is a shading 230 of the surface in Fig. 11.

[0046] Figure 20 shows a set of triangles 242, two prior art shadings 244, 246, and a shading of the present invention 248.

[0047] Figure 21 shows a sphere displaced with a checker texture 260, where all three vertices of a triangle are displaced by the same amount, and where a grouping and averaging approach produce an unsatisfactory shading.

[0048] Figure 22 shows a rendering 270 of the displacement shown in Fig. 21, improved by using the normals before displacement.

[0049] Figure 23 shows hardware of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0050] Figure 2 shows a flowchart of a method according to an embodiment of the invention. Initially, an object is input 60. The object is sampled 62 in the height field resulting in a height map. Following the sampling 62, the method detects features 64 in the height map. Based on the features, samples below a threshold are discarded 66. The remaining feature points are adjusted 68 and new points are added, possibly repeated k times. Finally the feature points are used to build a smaller triangulation 70.

[0051] Figure 3 shows an original surface 80 including a sinusoidal wave displacement area 82 colored white, and a non-displaced area 84 colored black. The displacement area 82 is an area that will be offset by a displacement function. The non-displaced area is an area of the original surface 80 that remains unchanged. The present invention offsets a surface, as for example original surface 80, by analyzing a height field to find details of the height field. An original surface is divided into triangles (tessellated), or some other shape or polygon. Each triangle is uniformly sampled using the height field, generating a two-dimensional height map for each triangle. The height map of a triangle is used to generate a two-dimensional feature map of the triangle. The feature maps for the triangles are adjusted according to their features. The two-dimensional feature maps are triangulated to form a final mesh.

[0052] Figure 4 shows a two-triangle original tessellation of the original surface 80 seen in Fig. 3. As in Fig. 3, original surface 80 includes a sinusoidal wave displacement area 82 colored white, and a non-displaced area 84 colored black. In rendering applications, the surface geometries that are to be displaced are often described separately from displacement maps and texture maps. This separation permits maps and shaders to be layered onto the original surface geometry, which is usually parameterized. Curved original surfaces, such as Non-Uniform Rational B-Splines (NURBS) and subdivision surfaces, are usually approximated by a tessellation. Therefore, the displacement process generally starts with an original surface that is comprised of a set of triangles called an original tessellation, as shown for example in Fig. 4. The vertices of an original tessellation are preferably dense enough to represent the original surface, but not dense enough to represent a displacement of the surface. Examples of these vertices are shown in Fig. 4 by vertices 86.

[0053] Figure 5 shows an example of a triangle 100 in an original tessellation, where the triangle has a sample point grid, defined by axes 102, 104, and origin point 106, that is used in generating a height map for the triangle. The diagonal line of the triangle is line 108. For each

triangle of an original tessellation, a local height map is generated by uniformly sampling the height field in the barycentric space of the triangle at the coordinates of each sample point, of which sample point 110 is an example. In the triangle 100 of Fig. 5, the points shown in the triangle would be sampled in the height field. This approach is preferred because it allows the displacement to be defined for complex shading networks, such as combinations of varied-resolution textures, or procedural textures. Other mapping techniques such as uv-mapping or projection mapping may be used to generate the height map of a triangle, and other sampling schemes may also be used.

[0054] Sampled grid points are generated for each triangle, and are preferably regularly and uniformly spaced, which facilitates simple and fast feature detection, and which also provides a natural filtering method that can be passed to the sampling method. The grid is created by first choosing an origin for the grid, for example origin point 106, where the origin is the triangle vertex that faces the longest triangle edge line 108. This choice improves the accuracy of later-discussed feature computations by minimizing oblique distortion introduced by the non-orthogonal coordinate system, which improves the layout of local neighborhoods of sample points used in the feature computations. The advantage of so choosing the origin can be seen by comparing Fig. 5 with Fig. 6. Figure 6 shows a triangle 120 with a grid based on an inferior origin 122 that is not opposite the longest side of the triangle 120, resulting in a grid that exhibits more oblique distortion than the grid in Fig. 5.

[0055] After an origin for a grid is chosen, the axes of the grid are uniformly sampled n+1 times, from the origin, to produce a grid of $\frac{1}{2}(n+1)(n+2)$ sample points. In other words, for each triangle, the number n defines a resolution of features that can be detected in the triangle, where each triangle has on the order of $\frac{n^2}{2}$ sample points. In Fig. 5, n = 8, and there are 45 sample points. Sample points of a grid, on and in a triangle, are discretely addressable as

[0056] $P_{i,j} = \left(\frac{i}{n}, \frac{j}{n}\right), \textit{where } i, j \in [0,n]; i + j \leq n$

[0057] The value of n may be set in various ways. The value of n can be set by a user, and the user may divide the original tessellation into regions requiring different n values. Such regions can be determined by painting, graphical delineation, or the like. The value of n can also be determined algorithmically. The value can be determined based on the point of view, a

feature size of the displacement map, and other context sensitive factors. The value of n can therefore vary from one triangle to the next, according to necessity. The number of sample points can also be determined using a preferred distance between sample points, in which case the value will not be the same for all triangles. For example, a user might specify a distance of 1 millimeter, and n for each triangle would be set to accommodate sample points spaced 1 millimeter apart. The value of n can also be set as a ratio of feature size.

[0058] Figure 7 shows triangle 120 with sample point $P_{i,j}$ that has a local neighborhood 130. For each sample point $P_{i,j}$, barycentric interpolation is used to compute the rendering attributes and sample the displacement function h. The rendering attributes may be for example texture coordinates and 3D point positions. When the displacement map is only a simple texture, the sampling may involve only a pixel lookup. Sampling complex displacements may require evaluating a full shading network. For each triangle, displacement values may be recorded in separate discretized height maps, where $h_{i,j} = h(P_{i,j})$ for each sample point in the grid of the triangle.

[0059] The sampled height map of each triangle is used to analyze in two dimensions displacement features or details of the height field that are in or near the triangle. The height map of a triangle is used to create an initial feature map for the triangle of the height map. A feature map indicates where features are located or oriented in or near a triangle, and includes for each sample point $P_{i,j}$, a feature metric $f_{i,j}$ and a feature orientation $o_{i,j}$. The feature metric $f_{i,j}$ of a sample point indicates whether there is enough detail at the sample point to justify using the sample point as a vertex when triangulating the feature points into a final surface mesh. The feature orientation $o_{i,j}$ of a sample point $P_{i,j}$ is a direction along which the feature point might be adjusted within the triangle (possibly off axis to the regular sampling grid) to better capture detail.

[0060] The feature metric $f_{i,j}$ for a sample point $P_{i,j}$ is a metric that indicates or measures how important point $P_{i,j}$ is for representing the detail of the displacement map. The feature metric $f_{i,j}$ can be computed from various heuristics, including combinations of derivatives and second derivatives of height field h and height values from the height map of neighboring and nearby sample points. The feature metric $f_{i,j}$ is used to eliminate from the feature map (and therefore from the ultimate displaced mesh) any points that do not add sufficient features or detail.

[0061] In a preferred embodiment, feature metric $f_{i,j}$ of a sample point $P_{i,j}$ is a sum of

approximate second derivatives of the displacement function h in different directions emanating from $P_{i,j}$. The second derivative h" is the local curvature or degree of curvature at a point of h. At a point $P_{i,j}$, $h_{i,j}$" equals or approaches zero when the height function around $P_{i,j}$ is locally flat. For such sample points, $f_{i,j}$ of $P_{i,j}$ is small or zero, and the point $P_{i,j}$ may be discarded or ignored as a feature point because it is not an important vertex for representing detail of the displacement map. The second derivative h" can be approximated in one dimension using equation (1), Taylor's series:

$$h''(x) \approx \frac{h(x+\Delta x)+h(x-\Delta x)-2h(x)}{(\Delta x)^2} \qquad (1)$$

[0062] Figure 8 shows triangle 120 with a sample point $P_{i,j}$ (gray) having neighboring points N(1) (hollow) and N(2) (black). The height map values of neighborhood points N(1), N(2) of $P_{i,j}$ are used to calculate $f_{i,j}$ at $P_{i,j}$. Local areas, or neighborhoods, of a point $P_{i,j}$ are defined and used to determine the local curvature feature metric of the point $P_{i,j}$. Informally, a neighborhood N(d) of $P_{i,j}$ is defined to be the set of grid points that are within d units or less of $P_{i,j}$ and are not on any line that connects $P_{i,j}$ to a point of N(d-1). For example, Fig. 8 shows $P_{i,j}$ as the center shaded point. In Fig. 8, the N(1) neighborhood of $P_{i,j}$ consists of the set of eight black points around $P_{i,j}$, and the N(2) neighborhood is the set of hollow points. The corners of the parallelogram (not shown) delineated by the hollow points are not included in N(2) because they are aligned with $P_{i,j}$ and the corner points of neighborhood N(1). Formally, a neighborhood of a point $P_{i,j}$ is defined as: $N(d)=\{\mathrm{P}_{i+k,j+l}, |k|<d, |l|<d, k \wedge l = 1\}$, where $k \wedge l$ is the greatest common divisor of *k* and *l*. Points in N(d) are discretely addressable.

[0063] Figure 9 shows four lines 140 defined by $P_{i,j}$ and its N(1) neighborhood. Preferably, point $P_{i,j}$'s feature metric $f_{i,j}$ is computed by summing the four Taylor approximations of $h_{i,j}$", at $P_{i,j}$ in the directions of the four lines 140 through $P_{i,j}$ that intersect pairs of opposing points in N(1), using for each direction the height map values for the corresponding opposing points. The feature metric calculation may be described mathematically with equation (2):

$$f_{i,j} = c_{1,0} + c_{0,1} + \tfrac{1}{2}\left(c_{1,-1} + c_{1,1}\right), \text{ where } c_{k,l} = \left|h_{i+k,j+l} + h_{i-k,j-l} - 2h_{i,j}\right| \qquad (2)$$

[0064] As previously noted, the value of $f_{i,j}$ of a point $P_{i,j}$ indicates or is a measure of how important $P_{i,j}$ is to representing or depicting details in the height field or displacement map. Low or zero feature metric values indicate corresponding sample points in the triangle that are in locally flat or planar regions of the height map, and which therefore tend not to be important or

necessary to depict or represent detail in the height map. Therefore, while calculating the feature map of a triangle, sample points with a feature metric equal or close to 0 are preferably discarded. Other thresholds or criteria may be useful, according to the circumstances.

[0065] In practical applications, it is often desirable to adjust the level of detail in a displacement map that will be reflected in the final mesh. For example, when a height function is a procedural fractal texture that has mathematically infinite detail, there is a need to select a level of detail of the texture, e.g. coarse, granular, or smooth. A threshold may be set, and if a point in a triangle represents a level of detail below the threshold, then it may be discarded, thereby further reducing the number of points in the mesh without significantly affecting the representation or portrayal of the desired level of detail.

[0066] Detail-level thresholds for displacements are preferably ratios of global maximums of feature heights and feature gradients of all of the triangles. In practice, it is preferable, while computing the height maps and feature maps, to track and store the global maximum height difference h_{max} of the height maps, and the maximum feature metric value, or maximum feature magnitude f_{max}., of the feature maps. The global maximum height difference h_{max} is the maximum difference in height between adjacent points in a height map. The maximum feature metric value f_{max} is simply the largest global feature metric of the feature maps. These global maximums may be used to determine detail-level thresholds, for example by using a ratio $r \in [0,1]$, which may be defined by a user to scale the global maximums.

[0067] The thresholds may be used to adjust the level of detail by discarding points that fall below the threshold, e.g. points that represent small or low levels of noise, or relatively locally smooth or planar areas of the displacement map. A detail-level threshold may also be used to reduce small noise by discarding all candidate feature points with an average height difference in N(1) that is smaller than $r\ h_{max}$. This reduces small noise and eliminates points not adding significant detail by discarding points with a feature metric lower than a generally small percentage of f_{max}. These points can be eliminated to significantly reduce the total number of points in the mesh without significantly affecting the detail of the height map. This elimination keeps the number of sample points low while still capturing precisely the shape and detail of the features.

[0068] Figure 10 shows a surface 150 generated with triangles that have had sample points removed based on their feature metric, but where the triangles have not been feature-adjusted.

The zipper effect artifact 152 visible along the edge of the "cliffs" in Fig. 10 is caused by the finite sampling density in each triangle. Refining the sampling density of the grid does not help to capture features that are not aligned on a grid; they do not coincide with any sample points generated up to this point. Even a refined grid may produce visible artifacts, although at smaller scales. These artifacts may be eliminated or reduced by adjusting sample points using a feature orientation.

[0069] Figure 11 shows a surface 160 generated with triangles used to generate Fig. 10, but with feature points adjusted (added and moved) based on features located with feature orientations. Area 162 exhibits less zipper effect than area 152 if Fig. 10. The surface 160 in Fig. 11 was generated using constrained triangulation discussed in detail further below. Because of the feature point adjustment, the surface 1600 lacks artifacts 152 in Fig. 10, and more accurately represents the displacement.

[0070] After the feature map of a triangle is calculated, and preferably after some low-detail points in the height and feature map have been eliminated accordingly, the height maps are used to calculate feature orientations $o_{i,j}$ for points $P_{i,j}$ in the triangles. The feature orientations may be added to the feature maps. Generally, a sample point $P_{i,j}$'s feature orientation $o_{i,j}$ is the direction from the point to a nearby feature or detail in the displacement map. More specifically, in a preferred embodiment, the feature orientation $o_{i,j}$ of a sample point $P_{i,j}$ is the direction from the sample point that has the greatest approximate rate of height change. In other words, a feature orientation $o_{i,j}$ is a direction from a sample point $P_{i,j}$ to a feature or feature detail in the height field that is near the sample point. Any method defining a function f from a height field, and a preferred direction o can be used, and is not restricted to any specific formula for f or o. More generally, the present invention can use a height field to find features and their directions, whatever the calculations or formulas may be.

[0071] Feature points in a triangle may be adjusted by using the feature orientations to move the feature points or add new ones. Stated another way, after insignificant sample and feature points have been eliminated as discussed above, the feature points identified in the feature map may be adjusted, using the feature orientations $o_{i,j}$, to more precisely capture the displacement shape. Preferably, this adjustment is performed by detecting in the height field high curvature areas and feature edges and then moving or adding feature points accordingly.

[0072] Feature point adjustment without first eliminating flattish sample points may be used by itself to displace a surface, however, feature point adjustment is preferably performed in

conjunction with or after the elimination of points based on their feature-metric, as discussed above. This approach is preferable because the values in the height map and feature map (e.g. height values of sample points) that are used during the feature-metric processing may also be used for feature orientation adjustment. Furthermore, fewer calculations are necessary because there is fewer points in the triangles to be adjusted based on feature orientation; points have been eliminated by the feature-metric adjustment and or by detail threshold adjustment.

[0073] In a preferred embodiment, feature point adjustment starts with calculating the feature orientations for the raw feature points. A feature orientation of a sample point $P_{i,j}$ is the direction from $P_{i,j}$ which preferably has the greatest rate of height change, although other measures may be used to determine vertices, as previously discussed. A discrete gradient computation of h at $P_{i,j}$ may be used for $P_{i,j}$'s feature orientation $o_{i,j}$. Preferably, the sixteen discretized directions of the N(2) neighborhood are used for the computation. This approach is sensitive to discretization errors; the eight N(1) neighbors tend to produce an imprecise direction. Consequently, for points that have a well defined N(2) neighborhood in the triangle, all 16 N(2) directions are used. However, when N(2) of $P_{i,j}$ is not fully contained in a triangle, N(1) may used instead, because testing has shown that it is usually more numerically accurate to ignore missing directions than to extrapolate the height values outside of the triangle. For these non-N(2) sample points, N(1) is contained (well defined) in the triangle, with the exception of those points $P_{i,j}$ that are next to (but not on) the diagonal triangle edge (e.g. line 108 in Fig. 5). These diagonal-adjacent points have N(1) neighborhoods with one point outside the triangle. For these neighborhoods, the discrete gradient in the direction of the missing neighborhood point may be estimated by using the average of the two discrete gradients in the direction of the two N(1) neighborhood points that lie on the edge. Feature orientation is generally not needed or calculated for points on triangle edges.

[0074] By using least squares minimization, a linear function is fit to the 16 samples $h_{i,j}$ (or $f_{i,j}$) of N(2) (or the 8 samples of N(1), as the case may be). A linear function is fit to the samples $h_{i,j}$ around Pi,j, weighted by the inverse of their distance. The gradient of this linear function is proportional to formula (3):

$$o_{i,j} = \tfrac{1}{16}\sum\nolimits_{(k,l)\in N(2)} (h_{i+k,j+l} - h_{i,j}) \frac{1}{\sqrt{k^2+l^2}} \begin{pmatrix} k \\ l \end{pmatrix} \qquad (3)$$

[0075] The formula above is for points with well-defined N(2) neighborhoods in the triangle. For those points $P_{i,j}$ using neighborhood N(1), the equation sum is divided by 8 rather than 16,

and k and l are elements of N(1) rather than N(2). For those points $P_{i,j}$ with a point of N(1) outside the triangle, the summation term for that missing point is estimated using $\frac{1}{2}(h_{i,j+1} + h_{i+1,j})$, rather than $(h_{i+k,j+l} - h_{i,j})$.

[0076] Feature orientations are used to adjust the feature points. Figure 12 is a view above sample points in a triangle, showing the 8 neighborhood points N(1) (peripheral solid points) of sample point $P_{i,j}$, and a line segment $L_{i,j}$ which passes through the sample point $P_{i,j}$ in the direction of $P_{i,j}$'s feature orientation $o_{i,j}$, and on which are shown; the original position of the sample point (hollow circle $P_{i,j}$), the 2m (8) height samples (grey points P_{2m}), two of which are the adjusted location of $P_{i,j}$ (gray circle $P'_{i,j}$) and the sample point added at an extrema of line $L_{i,j}$ (gray square point $P''_{i,j}$). Figure 13 is a profile view of Fig. 12, showing the curvature of line $L_{i,j}$ in the height field with points corresponding to those in Fig. 12.

[0077] Starting with line $L_{i,j}$, which passes through $P_{i,j}$ in the direction of feature orientation $o_{i,j}$ and is bounded by the neighborhood N(1), 2m height sample points (P_{2m}) may be taken uniformly along $L_{i,j}$. A locally flat area around the sample point $P_{i,j}$ is checked for by using equation (1) to approximate h" for $P_{i,j}$ and the 2m samples along line $L_{i,j}$. When h"($P_{i,j}$) is below a threshold, it is moved or adjusted along $L_{i,j}$ to the closest of the 2m points that has a sufficiently large second derivative (i.e. above the threshold). In other words, if $P_{i,j}$ is in a locally flattish area (its h" in the direction of its $o_{i,j}$ is small), then it is moved along $L_{i,j}$ to a sample point $P'_{i,j}$ (chosen from among the 2m points) which has a less flattish (larger h") local area. Arrow 172 in Figs. 12 and 13 depicts a movement of $P_{i,j}$ to $P'_{i,j}$.

[0078] Figure 14 shows a plane surface 180 displaced with a ring texture or displacement map, where feature points in triangles were moved according to their feature orientation but where new feature points were not added at extrema. Artifacts 182 are visible on the top and at the base of the ring. The movement of feature points is not sufficient to capture the top profile of the ring or the curved area along the bottom of the ring. Adding vertices (or feature points) at high curvature locations solves the problem. If the sample point $P_{i,j}$ that is being moved or adjusted happens to be on the edge of a triangle, then it is preferably moved along the triangle edge rather than along $L_{i,j}$, thus preventing cracks or gaps between triangles.

[0079] While adjusting a point $P_{i,j}$ using $L_{i,j}$, it is also convenient to introduce new feature points (vertices) at extrema of the second derivative h" along line $L_{i,j}$, as for example point $P''_{i,j}$, shown in Figs. 12 and 13. An extrema may generally be determined according to h" values

along $L_{i,j}$; the greater the h" value for one of the 2m points on $L_{i,j}$, the more likely that it is an extrema candidate.

[0080] Figure 15 shows the image of Fig. 14 after vertices have been added to extrema on $L_{i,j}$, thereby improving the representation of the profile and base of the ring. When the moved and/or new points are not located precisely enough, the adjustment operation can be repeated k times to move or adjust sample points closer to features. In one implementation, this can be a parameter set by the user. The idea is to define n to represent the size of the smaller feature the user does not want to miss, and (k,m) represents the precision of the feature shape. Using k>1 is a way to reach the same precision with a smaller m, and faster computations. In practice k=2 or 3 are the best values. Repetitive adjustment (setting k>1) is preferable to increasing the number m, and quickly reaches the same precision with a small m. A $\frac{1}{m}$ smaller search range is used each time the operation is repeated. That is to say, around the shifted sample point progressively smaller segments of $L_{i,j}$ are uniformly sampled. For example, if 8 sample points (m=4) are used in the first iteration (as shown in Figs. 12 and 13), then on the second iteration the 8 sample points would be uniformly distributed around $P'_{i,j}$ and the distance between the sample points would be 1/4th the distance of the first iteration. Continuing the example, in Fig. 12 the segment from point $P_{i,j}$ to point 174 would be uniformly sampled with 8 points. With this method, the effective placement resolution is proportional to triangle size divided by nm^k, while using only $O(kmn^2)$ samples, whereas a brute force micropolygon approach would require $O((nm^k)^2)$ samples. New sample points at extrema may or may not be added with each iteration.

[0081] The value of m may be set in various ways. The value of m can be set by a user, and the user may divide the original tessellation into regions requiring different m values. Such regions can be determined by painting, graphical delineation, or the like. The value of m can also be determined algorithmically. The value can be determined based on the point of view, a feature size of the displacement map, and other context sensitive factors. The value of m can therefore vary from one triangle to the next, according to necessity. The number of sample points can also be determined using a preferred distance between sample points, in which case the value will not be the same for all triangles. For example, a user might specify a distance of 1 millimeter, and m for each triangle would be set to accommodate sample points spaced 1 millimeter apart. The value of m can also be set as a ratio of feature size.

[0082] After the feature points (vertices) have been finally determined in the two-

dimensional triangles of the original tessellation, the points may be triangulated to create a final mesh surface. For every triangle T, all of the feature points belonging to a triangle are collected. Cracks along shared edges may be prevented by including in the collection of feature points for a triangle feature points that are part of another triangle and yet are located on an edge shared by the other triangle and the triangle being processed, possibly including feature points added to the other triangle by feature-based adjustment.

[0083] The collected points for a triangle are locally triangulated by inputting their barycentric coordinates to a constrained two-dimensional Delaunay triangulation. The constraints, which may be defined as line segments $\overline{P'_{i,j}\, P'_{k,l}}$ between adjusted feature points, are a way of taking the height field and its features into account during the triangulation step. Figure 16 shows a displaced surface 200 with cracks 202 produced by a standard Delaunay triangulation. The cracks in Fig. 16 occur because the unconstrained Delaunay triangulation builds triangles joining high and low points. In other words, the points in Fig. 16 are well located but poorly connected.

[0084] Figure 17 shows a closer view of the cracks 202 shown in Fig. 16, as seen from another angle. Figure 18 shows a view of surface 220 with edges 222 (white lines) defined by a feature border. The cracks 202 produced by a triangulation that joins high and low points can be avoided by forcing the triangulation to include the edges 222 defined by the feature border. These constraining feature borders or edges may be found by, for a feature point, looking for neighbor points in the N(2) set that have, within a small threshold, a height close to the height of $P_{i,j}$. When several points in N(2) match the criteria, the segment of those points (to $P_{i,j}$) that is most orthogonal to the discrete gradient $o_{i,j}$ of point $P_{i,j}$ is selected as a segment of a border edge. This process creates a set of segments that together build contour lines (similar to iso-height lines in a topographic map) that fairly represent the height map. Figure 18 shows the connectivity hints, or edges 222, drawn as white segments. Delaunay triangulation may then be constrained by the contour lines or edges, thereby avoiding cracks and other artifacts.

[0085] The Delaunay triangulation constrained by feature borders creates a set of new triangles T_i to replace the original tessellation triangle T. As a result of adding constraints, the constrained triangulation may introduce new vertices at the segment intersections, if there are any. Accordingly the displacement map must be sampled for these added points. Furthermore, constrained triangulation may create long triangles with poor aspect ratios. These long triangles do not generally produce visible artifacts when they are rendered. However, a more balanced

triangulation may be produced by adding more feature points, at a cost of creating more triangles in the triangulation.

[0086] After triangulation, all of the triangles T_i may be built into a single object, as shown for example in Fig. 11. The vertices along the common edges are shared, allowing smooth shading. At this stage, a complete mesh of a displaced surface has been built and vertex normals for the surface may be computed. Figure 19 is a shading 230 of the surface in Fig. 11. In building the normals of a displaced surface, sharp feature edges, where necessary, are preferably produced by associating multiple normals with each vertex, depending, for a given vertex, on the orientation of the triangles connected to the vertex. A partition of the triangles around a vertex is built by grouping together triangles with similar orientation: two triangles are in the same group if their normals form an angle smaller than a given value α_0. Triangle normals are weighted by triangle size, and the normals in a group are then averaged.

[0087] Figure 20 shows a set of triangles 242, two prior art shadings 244, 246, and a shading of the present invention 248. The set of triangles 242 is shown shaded using three techniques. Shading 244 is the result of shading triangles 242 using a single averaged normal at the vertex. Shading 246 is a shading where each triangle has its own normal. The shading of the present invention 248 uses the grouping and weighted average approach discussed above.

[0088] Figure 21 shows a sphere displaced with a checker texture 260, where all three vertices of a triangle are displaced by the same amount, and where a grouping and averaging approach produce an unsatisfactory shading. Because all three vertices of a triangle are displaced by the same amount, the original vertex normal before displacement is more accurate than a triangle normal. Figure 22 shows a rendering 270 of the displacement shown in Fig. 21, improved by using the normals before displacement.

[0089] Figure 23 shows hardware of the present invention. The present invention is included in a system 280, such as depicted in Fig. 23, which includes a display 282 upon which an output of the present invention may be displayed. A computer 284, preferably of high performance workstation type, performs the processes described herein and an input device 286, such as a mouse or stylus with pad, is used to control functionality described herein. The system 280 also includes storage (not shown), such as disc storage and RAM in which the processes of the present invention can be stored and on which the processes can be distributed. The processes can also be distributed via a network, such as the Internet.

[0090] The present invention has been described with respect to displacing and rendering objects by adaptively refining the original object geometry in a user-controllable manner according to the salient features of the displacement map. This approach presents a general solution for displacement mapping in ray-tracing, hardware-accelerated rendering (e.g. for games), or when complete meshes are required. Displacement geometries may also be pre-computed and subsequently used as high-quality geometric objects.

[0091] The order of triangle processing can be varied. Each triangle can be fully processed in turn, one after the other, where each triangle is in turn height-mapped, feature-mapped, and triangulated. Also, all triangles can be height-mapped, then all are feature-mapped, then all triangulated into a final surface mesh. Triangles may also be processed in parallel. Furthermore, it is possible to process a triangle taking into account features of a neighboring triangle that has already been processed. These approaches can also be used in combination.

[0092] The present invention may also be used to sculpt objects with paint-based techniques. With hardware acceleration, it is possible to paint a displacement map onto an object, whereby the geometry of the object adapts in real-time to changes in the map.

[0093] In cases where the inverse parametric map between texture space and object space is known, for example a uv-mapped file texture, it is beneficial to perform feature analysis directly in texture space and back-project the result to object space. In addition to using a threshold to detect features, it is also efficient to use error accumulation along a Peano curve, or to use a probabilistic approach.

[0094] Although the invention has been described with uniform sampling, the sampling may also be non-uniform. For example, sampling may be driven by triangle size or aspect ratio. View dependent criteria may also be introduced to define and adjust the feature points.

[0095] Although processes of the invention have been described using neighborhoods N(1) and N(2), other sets of points for neighborhoods may also be used. Neighborhoods can be chosen dynamically, etc.

[0096] Although f and o have been defined with reference to an embodiment discussed above, f and o may be computed with other formulas or algorithms.

[0097] The many features and advantages of the invention are apparent from the detailed specification and, thus, it is intended by the appended claims to cover all such features and advantages of the invention that fall within the true spirit and scope of the invention. Further,

since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation illustrated and described, and accordingly all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.